871. Acceleration improvement for coil winders of RRRCC type by variable input speed method

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Abstract. This paper aims to propose a variable speed approach for minimizing the output acceleration of coil winding mechanism, and verify its feasibility by simulation. Firstly, the structure of RRCCC winding mechanism is described. Then, its kinematic dimensions are examined. Furthermore, the design approach of the variable speed trajectory is presented. Finally, the feasibility and validity of the proposed approach are investigated by Kinematic simulation. The results show that the proposed approach can effectively reduce the output acceleration; therefore the vibration and the inertial force of the shuttle can be minimized.

Keywords: variable speed method, winding mechanism, vibrations, acceleration optimization.

Introduction

A coil winder refers to a machine that warps wires on an object with specific shape [1]. It can be classified as general purpose type and specific purpose type. The former can wrap wires on many kinds of parts; nevertheless the later can only do on a few parts with specific shape. It is extensively used in production and manufacturing of various parts, e.g., motor coils, textile, heaters, and cables. Nowadays, it is one of important and indispensable automatic machinery.

The dynamic characteristics of the winder play an essential role in the quality of its products. The unwanted higher acceleration of the shuttle will cause the breakage of the enameled wire that it wrapped. In addition, the fluctuation of the acceleration will produce vibration, and lead to loose winding. Therefore, it is a critical topic to improve the acceleration of the winder.

In 1922, Gysel [2] presented a mechanism that can warp wire internally, which can be simplified to be a RCRC over-constrained mechanism. It has advantages of simple structure and low cost. In 1922 and 1934, Herrick [3] and Laib [4] employed cam mechanisms and linkages to stator coil wide, respectively. However, its structure is complicated. In 1953, Harvey [5] proposed a stator coil winder using gear trains and linkages. In 1962, Gorski et al. [6] applied conjugate cams to the stator coil winders for controlling the rectilinear and rotary motion of the shuttle. In 1966, Moore [7] proposed a stator wider by using gear train. In 1979, Finegold [8] utilized Scotch yoke mechanism and cam mechanism to produce the motion of the shuttle. In 1979, Kamei [9] proposed a coil winder with a differential. In 2011, Hsieh & Tsai [1] investigated the feasibility of a new coil winder with a spatial RSPC mechanism by conducting kinematic simulation. From the literature above, only a few patents and introductory literature on the coil winders could be found. No rigor investigation on the design of the coil winder. Needless to say, the improvement of its performance.

The purpose of this study is to propose a variable speed approach for improving the output acceleration of coil winding mechanism. First, RRRCC winding mechanism will be introduced. Then, kinematic analysis will be carried out. Next, a design approach for the variable input speed trajectory will be proposed. Furthermore, the canonical form of optimization for the trajectory will be also formulated. Finally, a design example will be given for illustration, and the effectiveness of the proposed approach will be investigated.

RRRCC Winding Mechanism

Fig. 1 shows the schematic of the shuttle's motion for a stator coil winder. The shuttle will reciprocate and oscillate simultaneously at the ends of its strokes to warp the enameled wire on the upper and lower molds, and then guide the wire into the proper position in the stator. Spatial mechanisms are widely adopted to be the mechanism of coil winders. Since it can drive, by using only a rotating motor, the shuttle to translate and rotate simultaneously. In this study, a spatial RRRCC coil winding mechanism is investigated. Its schematic diagram is shown in Fig. 1, where revolute pairs are located at joints A, B, and C and cylindrical pairs are located at joints D and E.

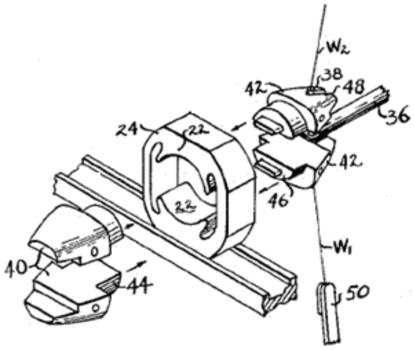

Fig. 1. Coil winding [7]

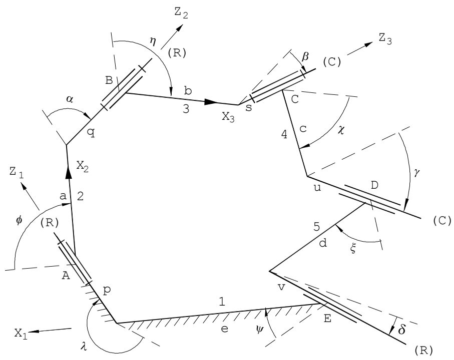

Fig. 2. RRRCC coil winding mechanism

Kinematic Analysis

Since the dual number notation is a compact form for representing the geometry between two lines, it is used for the subsequent analyses in the study. The kinematic analysis is performed as what follows:

1. Defining the geometry

The mechanism is completely defined by the following dual number notations:

(1) Between adjacent pairing axes:

$$\begin{aligned} \hat{\alpha} &= \alpha + \varepsilon a \\ \hat{\beta} &= \beta + \varepsilon b \\ \hat{\gamma} &= \gamma + \varepsilon c \\ \hat{\delta} &= \delta + \varepsilon d \\ \hat{\lambda} &= \lambda + \varepsilon e \end{aligned} \tag{1}$$

where $\hat{\alpha}$ is the dual angle between $\mathbf{z}_1$ and $\mathbf{z}_2$, α is the twist angle, and a is the link length, and the other four dual angles can be similarly defined. In addition, ε is the dual unit having the property $\varepsilon^2 = 0$ [10].

(2) Between adjacent common perpendiculars:

$$\begin{aligned} \hat{\phi} &= \phi + \varepsilon p \\ \hat{\eta} &= \eta + \varepsilon q \\ \hat{\chi} &= \chi + \varepsilon s \\ \hat{\xi} &= \xi + \varepsilon u \\ \hat{\psi} &= \psi + \varepsilon v \end{aligned} \tag{2}$$

where $\hat{\phi}$ is the dual angle between $\mathbf{x}_1$ and $\mathbf{x}_2$, ϕ is the angular displacement of joint A, and p is the offset between $\mathbf{x}_1$ and $\mathbf{x}_2$, and the other four dual angles can be similarly defined.

There are seven variables in Eq. (2). Angles ϕ and ψ are the input angle and the output angle, respectively, v is the output translation. The other variables are angles η, χ and ξ, and translation u. There are 13 constant kinematic dimensions, 10 quantities (a, b, c, d, e; α, β, γ, δ, λ) in Eq. (1) and 3 quantities (p, q, s) in Eq. (2), necessary to specify completely a five-bar RRRCC winding mechanism.

2. Establishing loop-closure equation by dual matrix

From Fig. 2, the loop-closure equation of the linkage, expressed in dual matrix, can be given by:

$$[\hat{\varphi}_3][\hat{\alpha}_1][\hat{\eta}_3][\hat{\beta}_1][\hat{\chi}_3][\hat{\gamma}_1][\hat{\xi}_3][\hat{\delta}_1][\hat{\psi}_3][\hat{\lambda}_1] = [I] \tag{3}$$

where:

$$\left[\hat{\varphi}\right]_3 = \begin{bmatrix} C\hat{\varphi} & S\hat{\varphi} & 0 \\ -S\hat{\varphi} & C\hat{\varphi} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \left[\hat{\alpha}\right]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\hat{\alpha} & S\hat{\alpha} \\ 0 & -S\hat{\alpha} & C\hat{\alpha} \end{bmatrix}$$

$$\left[\hat{\eta}\right]_3 = \begin{bmatrix} C\hat{\eta} & S\hat{\eta} & 0 \\ -S\hat{\eta} & C\hat{\eta} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \left[\hat{\beta}\right]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\hat{\beta} & S\hat{\beta} \\ 0 & -S\hat{\beta} & C\hat{\beta} \end{bmatrix}$$

$$\left[\hat{\chi}\right]_3 = \begin{bmatrix} C\hat{\chi} & S\hat{\chi} & 0 \\ -S\hat{\chi} & C\hat{\chi} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \left[\hat{\gamma}\right]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\hat{\gamma} & S\hat{\gamma} \\ 0 & -S\hat{\gamma} & C\hat{\gamma} \end{bmatrix} \tag{4}$$

$$\left[\hat{\xi}\right]_3 = \begin{bmatrix} C\hat{\xi} & S\hat{\xi} & 0 \\ -S\hat{\xi} & C\hat{\xi} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \left[\hat{\delta}\right]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\hat{\gamma} & S\hat{\gamma} \\ 0 & -S\hat{\gamma} & C\hat{\gamma} \end{bmatrix}$$

$$\left[\hat{\psi}\right]_3 = \begin{bmatrix} C\hat{\psi} & S\hat{\psi} & 0 \\ -S\hat{\psi} & C\hat{\psi} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \left[\hat{\lambda}\right]_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\hat{\lambda} & S\hat{\lambda} \\ 0 & -S\hat{\lambda} & C\hat{\lambda} \end{bmatrix}$$

where C and S in the matrices denote the cosine and sine of the respective angles.

By rearranging the terms of Eq. (3), it yields:

$$[\hat{\lambda}_1][\hat{\varphi}_3][\hat{\alpha}_1][\hat{\eta}_3][\hat{\beta}_1][\hat{\chi}_3][\hat{\gamma}_1]] = ([\hat{\xi}_3][\hat{\delta}_1][\hat{\psi}_3])^{-1} \tag{5}$$

By substituting Eq. (1) and Eq. (2) into Eq. (5), we have:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \tag{6}$$

where a_{ij} and b_{ij} (i, j = 1~3) are the elements of the matrices in left side and right side of Eq. (6), respectively, and their expressions can be found in Refs. [11] and [12], are not listed here due to page limitation. In addition, the expressions of the coefficients omitted in the following equations can refer to the same references, and will not be stated additionally.

3. Finding the equation of the input and output angles

Equating a_{33} to b_{33} in Eq. (6), and followed by simplifying it, we have:

$$\begin{aligned}&C\hat{\gamma}(-S\hat{\alpha}(C\hat{\eta}C\hat{\lambda}S\hat{\beta}+C\hat{\beta}C\hat{\phi}S\hat{\lambda})+S\hat{\beta}S\hat{\eta}S\hat{\lambda}S\hat{\phi})+S\hat{\gamma}(C\hat{\chi}(C\hat{\phi}S\hat{\alpha}S\hat{\beta}S\hat{\lambda}+\\&C\hat{\beta}(-C\hat{\eta}C\hat{\lambda}S\hat{\alpha}+S\hat{\eta}S\hat{\lambda}S\hat{\phi}))+(C\hat{\lambda}S\hat{\alpha}S\hat{\eta}+C\hat{\eta}S\hat{\lambda}S\hat{\phi})S\hat{\chi})+\\&C\hat{\alpha}(-C\hat{\lambda}C\hat{\chi}S\hat{\beta}S\hat{\gamma}+C\hat{\beta}(C\hat{\gamma}C\hat{\lambda}-C\hat{\eta}C\hat{\phi}C\hat{\chi}S\hat{\gamma}S\hat{\lambda})+C\hat{\phi}S\hat{\lambda}(-C\hat{\gamma}C\hat{\eta}S\hat{\beta}+S\hat{\gamma}S\hat{\eta}S\hat{\chi}))=C\hat{\delta}\end{aligned} \quad (7)$$

where χ, ϕ and η are all the variables in Eq. (7). To eliminate η, the following transformations are introduced:

$$x_1 = \tan(\phi/2),\ x_2 = \tan(\varphi/2),\ x_2 = \tan(\eta/2) \quad (8)$$

Then, we have:

$$\cos\varphi = (1-x_1^2)/(1+x_1^2)\ ,\ \sin\varphi = 2x_1/(1+x_1^2) \quad (9)$$

$$\cos\varphi = (1-x_1^2)/(1+x_1^2)\ ,\ \sin\varphi = 2x_1/(1+x_1^2) \quad (10)$$

$$\cos\eta = (1-x_3^2)/(1+x_3^2)\ ,\ \sin\eta = 2x_3/(1+x_3^2) \quad (11)$$

By substituting Eqs. (8)-(11) into Eq. (7) and followed by separating into its primary and dual parts, we obtain:

$$A_2x_3^2 + A_1x_3 + A_0 = 0 \quad (12)$$

$$B_2x_3^2 + B_1x_3 + B_0 = 0 \quad (13)$$

where:

$$\begin{aligned}A_0 &= A_{02}x_2^2 + A_{01}x_2^2 + A_{00}\\A_1 &= A_{12}x_2^2 + A_{11}x_2^2 + A_{10}\\A_2 &= A_{22}x_2^2 + A_{21}x_2^2 + A_{20}\end{aligned} \quad (14)$$

and:

$$\begin{aligned}B_0 &= B_{02}x_2^2 + B_{01}x_2^2 + B_{00}\\B_1 &= B_{12}x_2^2 + B_{11}x_2^2 + B_{10}\\B_2 &= B_{22}x_2^2 + B_{21}x_2^2 + B_{20}\end{aligned} \quad (15)$$

The necessary and sufficient condition for the existence of at least one common root of Eq. (12) and Eq. (13) is [11]:

$$\begin{vmatrix}A_2 & A_1 & A_0 & 0\\0 & A_2 & A_1 & A_0\\B_2 & B_1 & B_0 & 0\\0 & B_2 & B_1 & B_0\end{vmatrix} = 0 \quad (16)$$

By solving Eq. (16), it yields:

$$C_8(x_1)x_2^{\ 8} + C_7(x_1)x_2^{\ 7} + C_6(x_1)x_2^{\ 6} + C_5(x_1)x_2^{\ 5} + C_4(x_1)x_2^{\ 4} + C_3(x_1)x_2^{\ 3} + C_2(x_1)x_2^{\ 2} + C_1(x_1)x_2 + C_0(x_1) = 0 \quad (17)$$

Eq. (17) is the equation of the input and output angles of the linkage, it is an eight-degree polynomial both in ϕ and ψ. This means that there are eight ways of configurations for the same set of kinematic dimensions.

4. Solving other displacement variable

η can be found by solving for $C\eta$ and $S\eta$ from Eq. (7). The primary and dual parts, respectively, are:

$$E_{11}S\eta + E_{12}C\eta = E_{13} \quad (18)$$

and:

$$E_{21}S\eta + E_{22}C\eta = E_{23} \quad (19)$$

Solving Eqs. (18) and (19) simultaneously, it yields:

$$S\eta = \frac{E_{13}E_{22} - E_{23}E_{12}}{E_{11}E_{22} - E_{21}E_{12}} \quad (20)$$

$$C\eta = \frac{E_{11}E_{23} - E_{21}E_{13}}{E_{11}E_{22} - E_{21}E_{12}} \quad (21)$$

Moreover, the other displacement variables can be found by equating other elements of Eq. (6). The primary parts of the elements 13 and 23 give, respectively:

$$S\chi = \frac{K_1}{S\gamma} \quad (22)$$

$$C\chi = \frac{K_2}{S\gamma} \quad (23)$$

where:

$$K_1 = S\delta S\psi(C\phi C\eta - C\alpha S\phi S\eta) + (S\delta C\lambda C\psi + C\delta S\lambda)(S\phi C\eta + C\alpha C\phi S\eta) + (C\delta C\lambda - S\delta S\lambda C\psi)S\alpha S\eta \quad (24)$$

$$K_2 = S\delta S\psi(-C\beta C\phi S\eta - C\alpha C\beta S\phi C\eta + S\alpha S\beta S\phi) + (S\delta C\lambda C\psi + C\delta S\lambda)(-C\beta S\phi S\eta + C\alpha C\beta C\phi C\eta - S\alpha S\beta C\phi) + (C\delta C\lambda - S\delta S\lambda C\psi)(S\alpha C\beta C\eta + C\alpha S\beta) \quad (25)$$

The primary parts of the elements 31 and 32 give, respectively:

$$S\xi = \frac{Z_1}{S\gamma} \quad (26)$$

$$C\xi = \frac{Z_1}{S\gamma} \quad (27)$$

where:

$$Z_1 = Y_1 C\psi - Y_2 C\lambda S\psi + Y_3 S\lambda S\psi \quad (28)$$
$$Z_2 = Y_1 C\delta S\psi + Y_2(C\delta C\lambda C\psi - S\delta S\lambda) - Y_3(C\delta S\lambda C\psi + S\delta C\lambda) \quad (29)$$

where:

$$Y_1 = S\beta C\phi S\eta + C\alpha S\beta S\phi C\eta + S\alpha C\beta S\phi \quad (30)$$
$$Y_2 = S\beta S\phi S\eta - C\alpha S\beta C\phi C\eta - S\alpha C\beta C\phi \quad (31)$$
$$Y_3 = -S\alpha S\beta C\eta + C\alpha C\beta \quad (32)$$

The dual parts of the elements 13 and 31 give, respectively:

$$u = \frac{R_u - cC\gamma S\chi}{S\gamma C\chi} \quad (33)$$
$$v = \frac{R_v - cC\gamma S\xi}{S\gamma C\xi} \quad (34)$$

where:

$$\begin{aligned} R_u = {} & [aS\alpha S\phi S\eta - p(C\alpha C\phi S\eta + S\phi C\eta) - q(C\alpha S\phi C\eta + C\phi S\eta)]S\delta S\psi - \\ & (C\alpha S\phi S\eta - C\phi C\eta)(dC\delta S\psi + sS\delta C\psi) + [-aS\alpha C\phi S\eta - p(C\alpha S\phi S\eta - C\phi C\eta) + \\ & q(C\alpha C\phi C\eta - S\phi S\eta)](S\delta C\lambda C\psi + C\delta S\lambda) + (C\alpha C\phi S\eta + S\phi C\eta) \\ & [d(C\delta C\lambda C\psi - S\delta S\lambda) - e(S\delta S\lambda C\psi - C\delta C\lambda) - S\delta C\lambda S\psi] + \\ & (aC\alpha S\eta + qS\alpha C\eta)(-S\delta S\lambda C\psi + C\delta C\lambda) - S\alpha S\eta[d(C\delta S\lambda C\psi + S\delta C\lambda) + \\ & e(S\delta C\lambda C\psi + C\delta S\lambda) - sS\delta S\lambda S\psi]Y_1 C\psi - Y_2 C\lambda S\psi + Y_3 S\lambda S\psi \end{aligned} \quad (35)$$

$$\begin{aligned} R_v = {} & C\psi[-aS\phi(S\alpha S\beta C\eta - C\alpha C\beta) + b(C\alpha C\beta S\phi C\eta - S\alpha S\beta S\phi + C\beta C\phi S\eta) + p(C\alpha S\beta C\phi C\eta + \\ & S\alpha C\beta C\phi - S\beta S\phi S\eta) - qS\beta(C\alpha S\phi S\eta - C\phi C\eta)] - sS\psi(C\alpha S\beta S\phi C\eta + S\alpha C\beta S\phi + S\beta C\phi S\eta) - \\ & C\lambda S\psi[aC\phi(S\alpha S\beta C\eta - C\alpha C\beta) - b(C\alpha C\beta C\phi C\eta - S\alpha S\beta C\phi - C\beta S\phi S\eta) + \\ & p(C\alpha S\beta S\phi C\eta + S\alpha C\beta S\phi + S\beta C\phi S\eta) + qS\beta(C\alpha C\phi S\eta + S\phi C\eta)] - \\ & (eS\lambda S\psi - sC\lambda C\psi)(C\alpha S\beta C\phi C\eta + S\alpha C\beta C\phi - S\beta S\phi S\eta) - S\lambda S\psi[a(C\alpha S\beta C\eta + S\alpha C\beta) + \\ & b(S\alpha C\beta C\eta + C\alpha S\beta) - qS\alpha S\beta S\eta] - (eC\lambda S\psi + sS\lambda C\psi)(S\alpha S\beta C\eta - C\alpha C\beta) \end{aligned} \quad (36)$$

5. Finding the output acceleration

As depicted in Fig. 3, the acceleration of the tip p at the winder nozzle a_p can be expressed as:

$$a_p = \sqrt{a_n^2 + a_t^2 + a_z^2} \quad (37)$$

where a_n, a_t and a_z are the normal, tangential, translational accelerations, respectively. And they can be calculated by:

$$a_n = r\dot{\psi} \quad (38)$$
$$a_n = r\ddot{\psi} \quad (39)$$
$$a_z = \ddot{v} \quad (40)$$

where r, $\dot{\psi}$, $\ddot{\psi}$ and $\ddot{v}$ are the half length of the nozzle, the angular velocity, the angular acceleration, and the translational acceleration of the shuttle, respectively. It is difficult to find the analytical form of the last three terms. However, they can be found by using finite difference after the numerical values of v and ψ have been solved from Eqs. (34) and (17).

Variable Input Speed Trajectory Design

An approach for the variable input speed trajectory design is proposed in the section. The design constraints and requirements are specified firstly. Then, the design steps are presented. Finally, the canonical form of the optimum design for the trajectory is formulated.

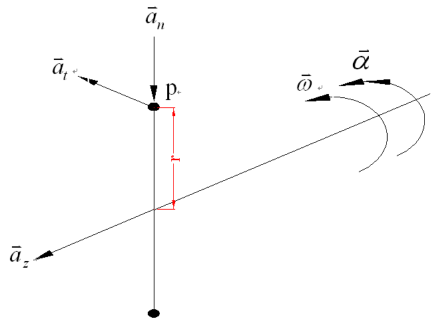

Fig. 3. Acceleration at the tip point of the winder nozzle

1. Design constraints and requirements

(1) The shape of the proposed major trajectory must be to the time axis with the output acceleration of the tip point p at the winder nozzle.
(2) Only Sine or Cosine function is employed.
(3) For acceleration continuity, the speeds at the beginning and the end points of a cycle must be equal and smooth.

2. Design steps

(1) Find the acceleration of a_p of the wider with constant input speed.
(2) According to design constraints and requirements (1), determine the shape and the frequency of the major trajectory based on a_p obtained in the step (1).
(3) Add a constant and a minor trajectory, an arbitrarily chosen Sine or Cosine function or more, to the major trajectory.
(4) Assign the amplitudes of trajectories, the frequencies and the phase shifts of the minor trajectory, and the constant as design variables.
(5) Find the optimum trajectory by performing optimum design.
(6) Verify by kinematic simulation.

3. Optimum design

Optimization can be defined as the process of finding the conditions that give the maximum or minimum value of a function [13]. Alternatively, optimization is finding a design in the feasible region which maximizes or minimizes the objective function. In order to perform optimum design, the design variables, the objective function, and constraints must be fully specified.

As described in Step (4), amplitudes, frequency and the phase shift, the constant could be set as the design variables x_i (i = 1~n). The purpose of the optimization for the coil winder is to improve the dynamic characteristics of the winder; therefore, the objective function is set as the acceleration of the tip point p, and can be expressed as:

$$\text{Min.} f(x_1, x_2, x_3, ..., x_n) = a_p(x_1, x_2, x_3, ..., x_n) \tag{41}$$

$$\text{Subject to} \quad \begin{array}{l} g_1 = lb_1 \le x_1 \le ub_1 \\ g_2 = lb_2 \le x_2 \le ub_2 \\ g_3 = lb_3 \le x_3 \le ub_3 \\ \quad \vdots \\ g_5 = lb_n \le x_n \le ub_n \end{array} \tag{42}$$

where g_i (i = 1~n) is the constraint equation, and lb_i and ub_i are its lower bound and the upper bound, respectively. Therefore, the canonical form of the optimization is formulated.

Design Example

A winder with the kinematic dimensions, listed Table 1, is given here to illustrate the proposed design process. By substituting these dimensions into Eq. (17) and Eq. (34), then ψ and v can be solved, respectively. Furthermore, $\dot{\psi}$, $\ddot{\psi}$ and $\ddot{v}$ can be found by employing finite difference. Moreover, the input angular speed $\dot{\psi}$ is set as 1 rev/sec (2π/sec). Finally by substituting the data above into Eqs. (38)-(40), then a_p can be found from Eq. (37), as shown in Fig. 4. It can be found that its frequency is equal to 4π/sec.

Table 1. Kinematic dimensions

Parameter \ Member no.	1	2	3	4	5
Twist angle (deg)	$\lambda = 270$	$\alpha = 270$	$\beta = 270$	$\gamma = 270$	$\delta = 90$
Link length (mm)	$e = 0$	$a = 76$	$b = 0$	$c = 0$	$d = 0$
Angular displacement (deg)	ϕ (input)	H	X	ξ	ψ (output)
Offset or linear displacement (mm)	$p = 103.9$	$q = 0$	$s = 0$	u	v (output)

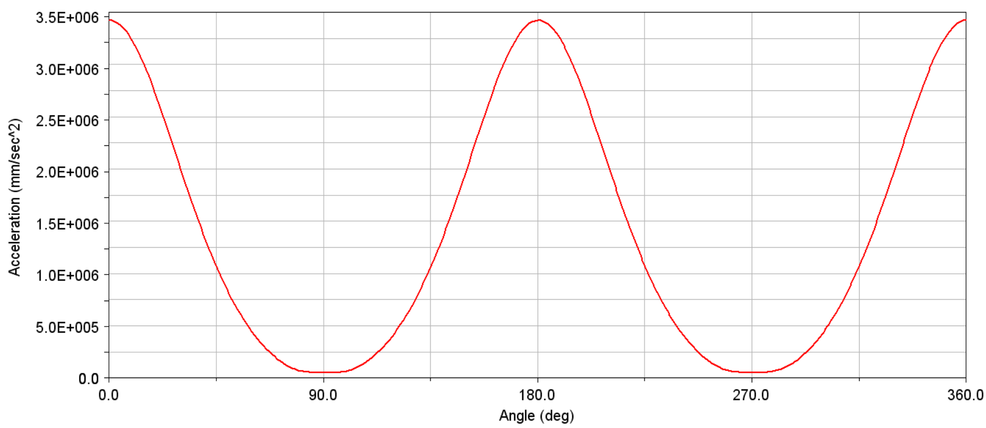

Fig. 4. Acceleration at the tip point of the winder nozzle (constant input speed)

Based on design step (2) in Sec. 3, the primary trajectory a_M can then be set as:

$$a_M = x_1 \cos(4\pi t + \pi) \tag{43}$$

To simplify the problem, let x_5 = 6.3, and then add a minor trajectory to form the proposed trajectory according to design step (3), then it yields:

$$\dot{\phi}(x_1, x_2, x_3, x_4) = x_1 \cos(4\pi t + \pi) + x_2 \cos(x_3 \pi t + x_4 \pi) + 6.3 \quad (44)$$

By integrating with respect to time, the input position ϕ can then be found. Moreover, substituting kinematic dimensions and $\dot{\phi}$ into Eq. (37), the objective function can be obtained. In addition, the constraint equations are set, by trial and error, as:

$$\begin{aligned} g_1 &= 0 \le x_1 \le 5 \\ g_2 &= 0 \le x_2 \le 5 \\ g_3 &= 0 \le x_3 \le 20 \\ g_4 &= 0 \le x_4 \le 2 \end{aligned} \quad (45)$$

Therefore, the optimization problem of the proposed design has been fully defined. It is a nonlinear constrained optimization problem, and this type of problem can be solved by using the fmincon function (SQP based, with medium scale option) in the optimization toolbox of Matlab software. Due to the ease of use, the optimization is conducted here by using ADAMS software. Fig. 5 depicts the solid model of the winder established with the specified dimensions, Then Eqs. (44) and (45) are set, respectively, as the objective function and the constraints for optimization. Finally, the optimization is performed by employing Design Evaluation Tools embedded in the ADAMS software. The optimized results are found to be x_1 = 2.2415, x_2 = 0.0640, x_3 = 3.5156, x_4 = 0.1397. By substituting them into Eq. (44), the optimized variable input speed trajectory is:

$$\dot{\phi} = 2.2415 \cos(4\pi t + \pi) + 0.0640 \cos(3.5156\pi t + 0.1397\pi) + 6.3 \quad (46)$$

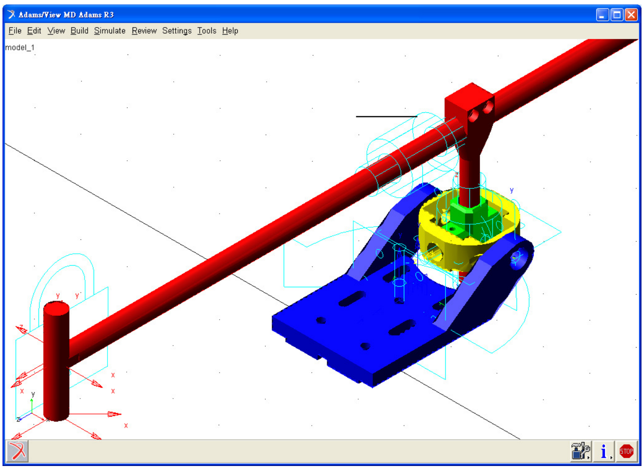

Fig. 5. Solid model of the RRCCC winder

In addition, Eq. (47) is set as the input of the winder, then the acceleration of the nozzle tip, shown in Fig. 6, can be obtain by performing simulation. It can be found that the maximum of the acceleration is reduced from 3.4600×10^6 to 1.8099×10^6 (mm^2/sec), about 47.69 % reduction. To compare the extent of the improvement, the area between the acceleration and the input angle axis, which means the sum of accelerations in a cycle, is calculated. It is found that areas before and after the optimization are 2.4026×10^8 and 1.4200×10^8, respectively, i.e., about 41.65 % area is reduced, therefore the inertial force and its induced vibration will be greatly decreased.

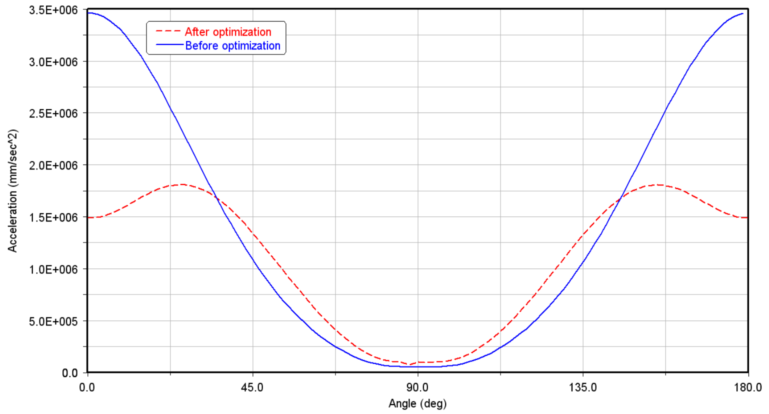

Fig. 6. Accelerations of the nozzle tip

Conclusions

In this work, a variable input speed approach for improving the dynamic performance of the RRRCC type coil winder has been proposed. Kinematic analysis has been conducted. Design steps of the variable input speed trajectory have been proposed, and the associated optimum design approach has been presented. A design example has been given for illustration, and its optimization and kinematic simulation have been conducted by utilizing ADAMS software. The result has indicated that the proposed new design can effectively reduce the maximum and the total of the acceleration at the nozzle tip. Therefore, the feasibility and effectiveness of the proposed have been verified.

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